Lawrence Berkeley National Lab
CBP seminar

July 12th 2013
10:30~11:30

High performance spin-polarized photocathode using GaAs/GaAsP strain-compensated superlattice

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Nagoya University

Outline

- Introduction
- Transmission-type GaAs/GaAsP strained superlattice photocathode
- High performance GaAs/GaAsP strain-compensated superlattice photocathode
- Conclusions

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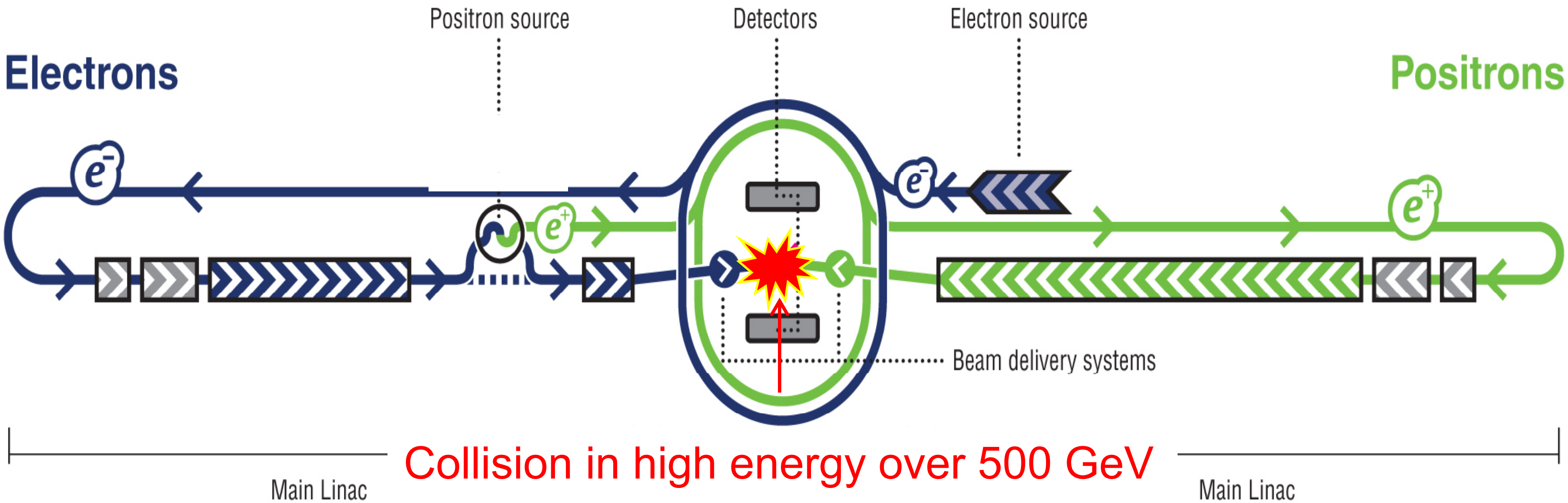
High energy physics

International Linear Collider (ILC)



Spin-polarized electrons play essential role to achieve
a better statistics of rare events.

Spin-polarization **> 80%**; Quantum efficiency **> Several %**.

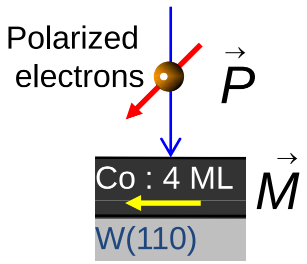
Spin-polarized LEEM

Spin-polarized electron beams are drawing much attention in several types of electron microscopy **for magnetic image**.

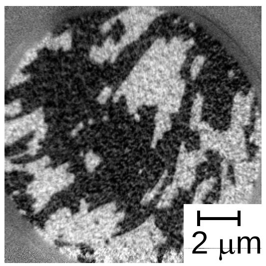
Spin-polarized LEEM observation

$$\boxed{A \propto \vec{P} \cdot \vec{M}}$$

A : Magnetic contrast
$\vec{P}$: Spin-polarization of electrons
$\vec{M}$: Magnetization of surface



SPLEEM Image



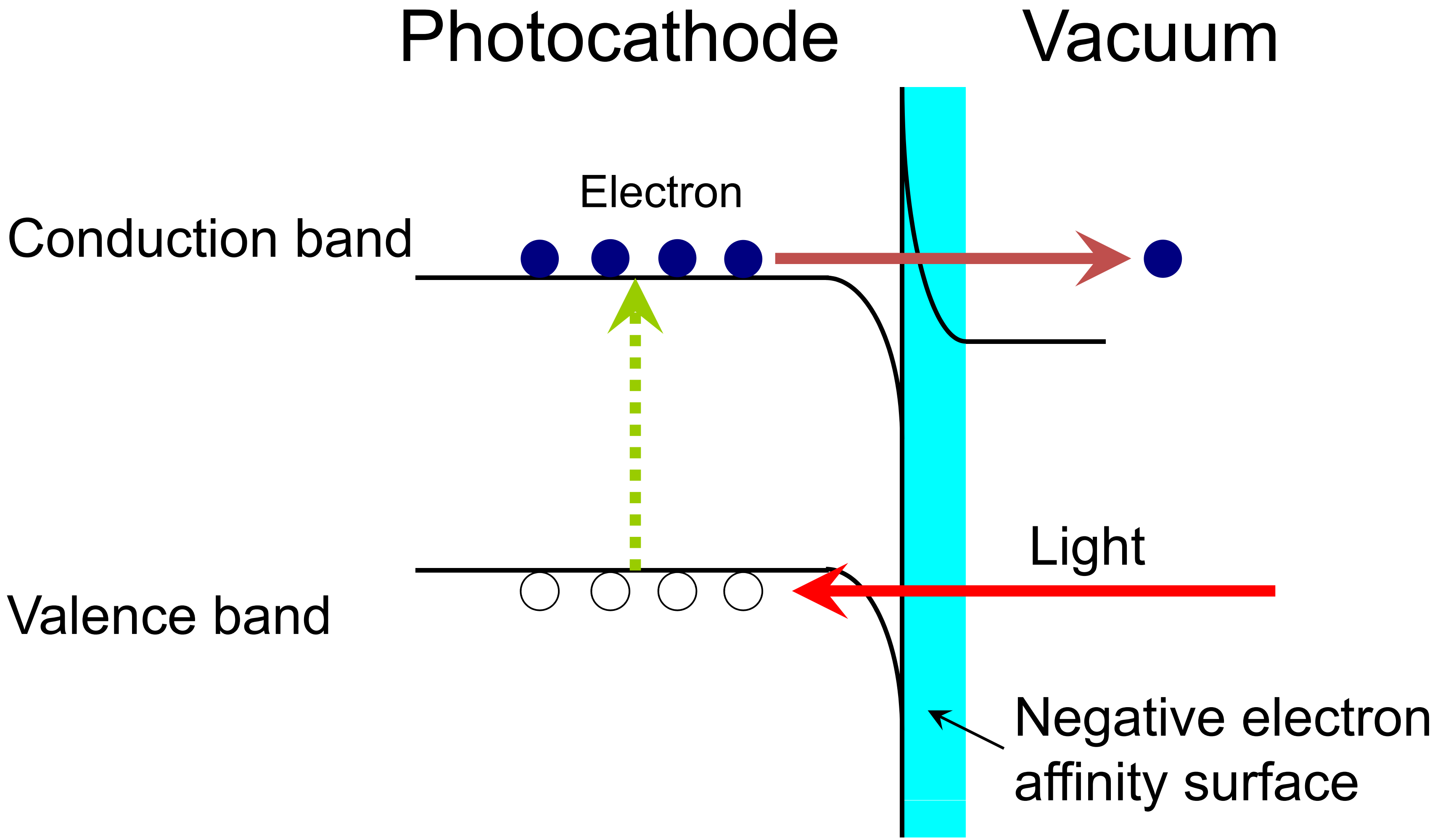
Electron beam for microscopy requires **two properties**:

- **High spin-polarization,**
  (for high image contrast)
- **High brightness**
  (for short exposure time)

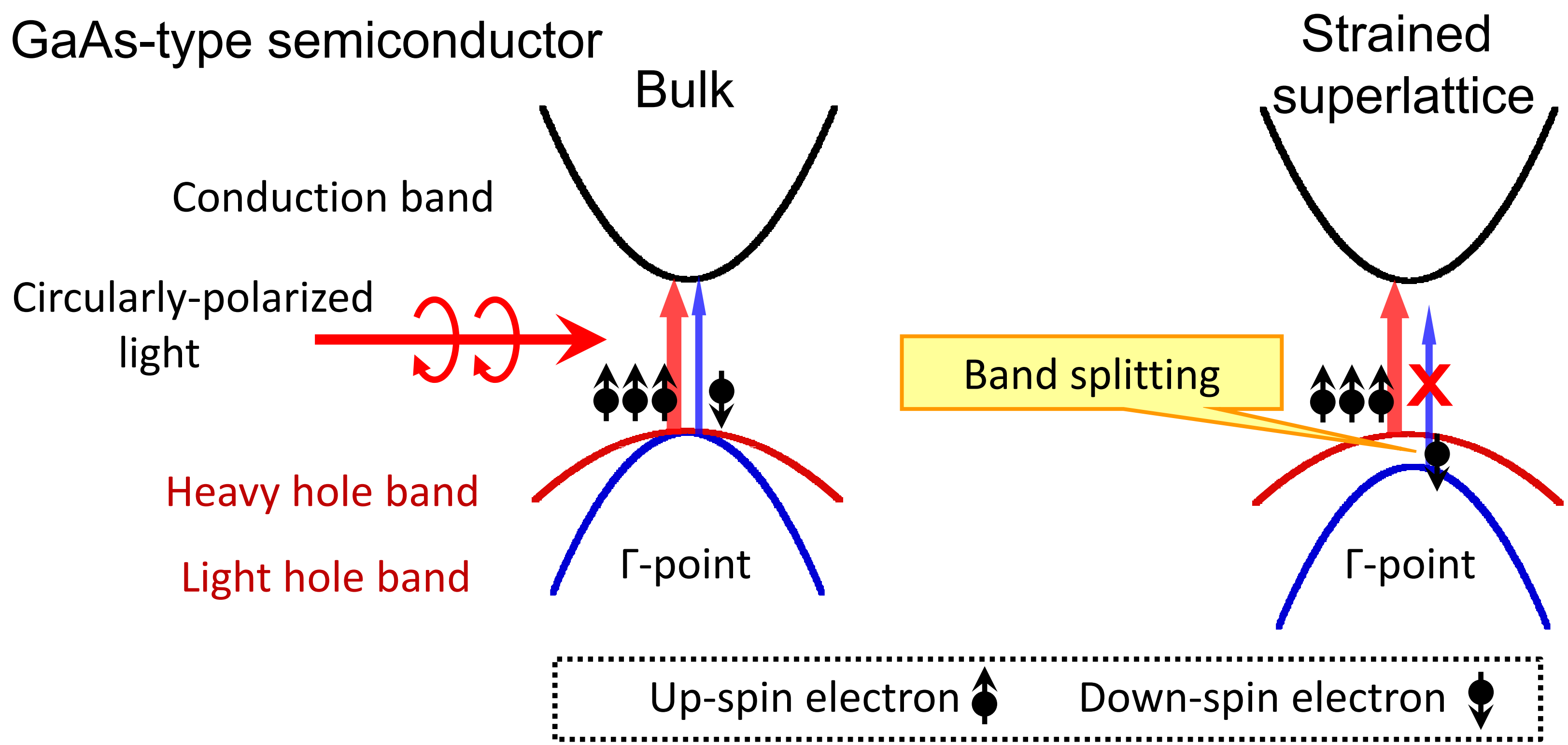
Conventional electron beam for SPLEEM:
Spin-polarization=20~30%
Brightness=1×10^{3} A·cm^{-2}·sr^{-1}
Exposure time=1-10 s

Real-time imaging with a high contrast:
Spin-polarization **>80%**
Brightness **>3×10^{5} A·cm^{-2}·sr^{-1}**
Exposure time**< 0.03 s**

Semiconductor photocathode



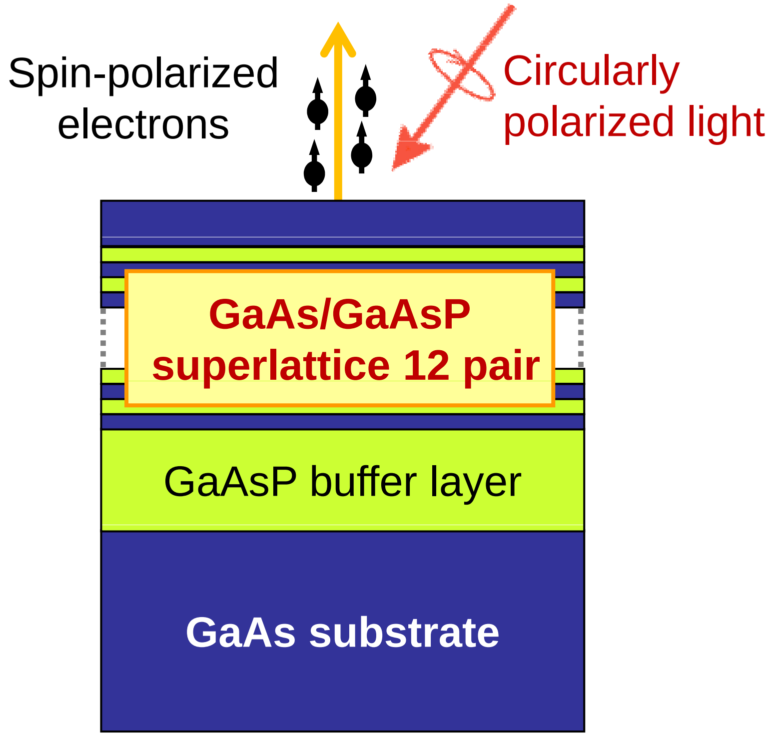
Semiconductor photocathode for spin-polarization



In GaAs type semiconductor, the heavy hole band and the light hole band degenerate at Γ-point and both up- and down-spin electrons are excited simultaneously by circularly polarized light.
If the valence bands are split, one type of electrons can be excited selectively.

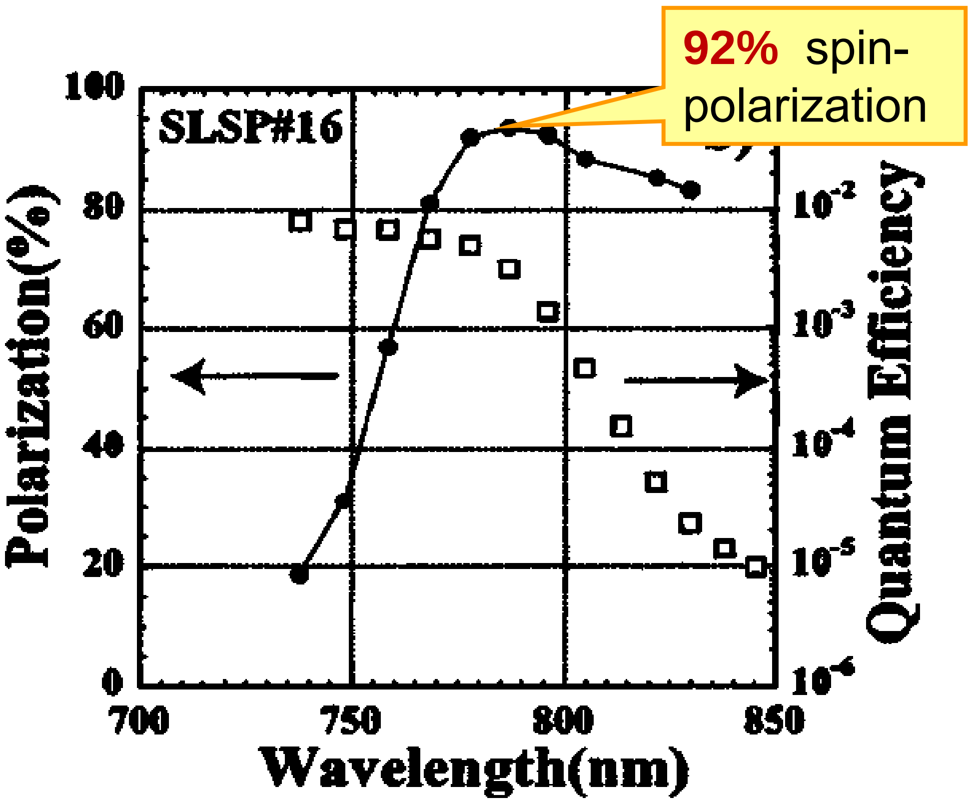
The band splitting allows excitation of one type of spin-polarized electrons.

GaAs/GaAsP strained superlattice



GaAs/GaAsP strained superlattice structure

Spin-polarization result



T. Nakanishi, Proceedings of LINAC (2002) 813.

Using GaAs/GaAsP strained superlattice grown on GaAs substrate, we have achieved **the highest spin-polarization of 92%.**

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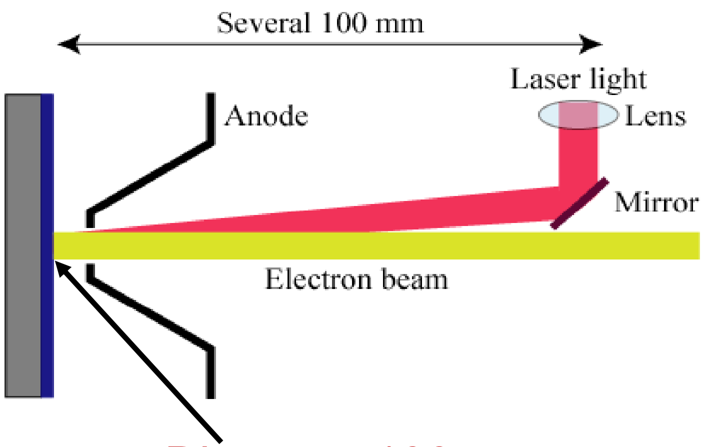
High brightness by highly focused laser light irradiation

$$\text{Brightness} = \frac{I}{S \cdot \Omega}$$

I: Electron beam current
S: Electron generation area
Ω: Electron beam solid angle

High brightness is obtained by reducing electron generation area.

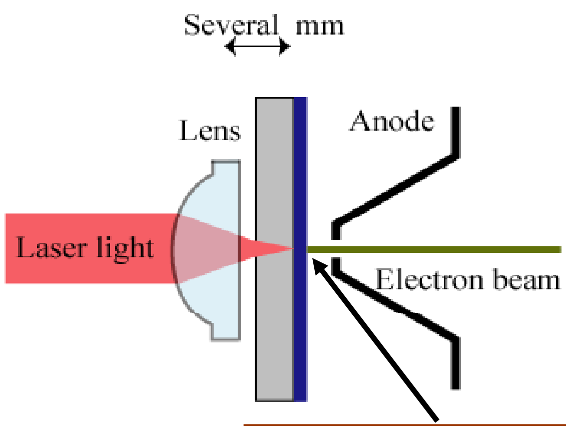
Conventional reflection-type



Diameter 100 μm

The pump laser light is difficult to be focused, and the electron generation area is large.

New transmission-type



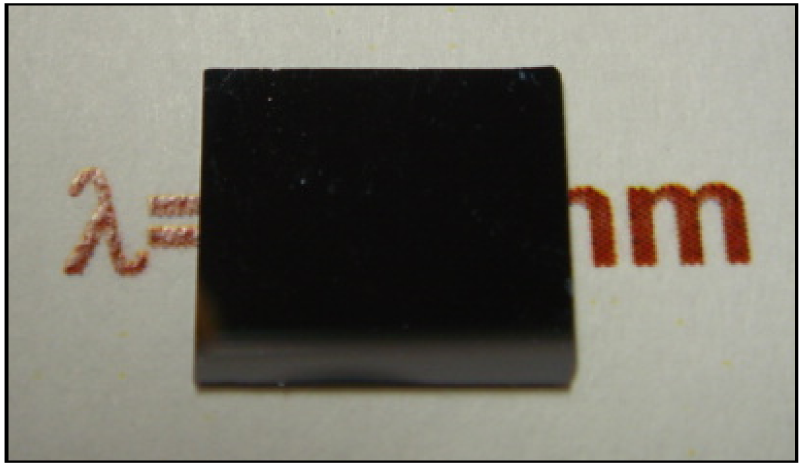
Diameter **1~2 μm**

The pump laser light can be highly focused, and the electron generation area is very small.

GaP substrate

Conventional reflection-type

New transmission-type



GaAs substrate
Band gap energy: 1.42 eV

GaP substrate
Band gap energy: **2.26 eV**

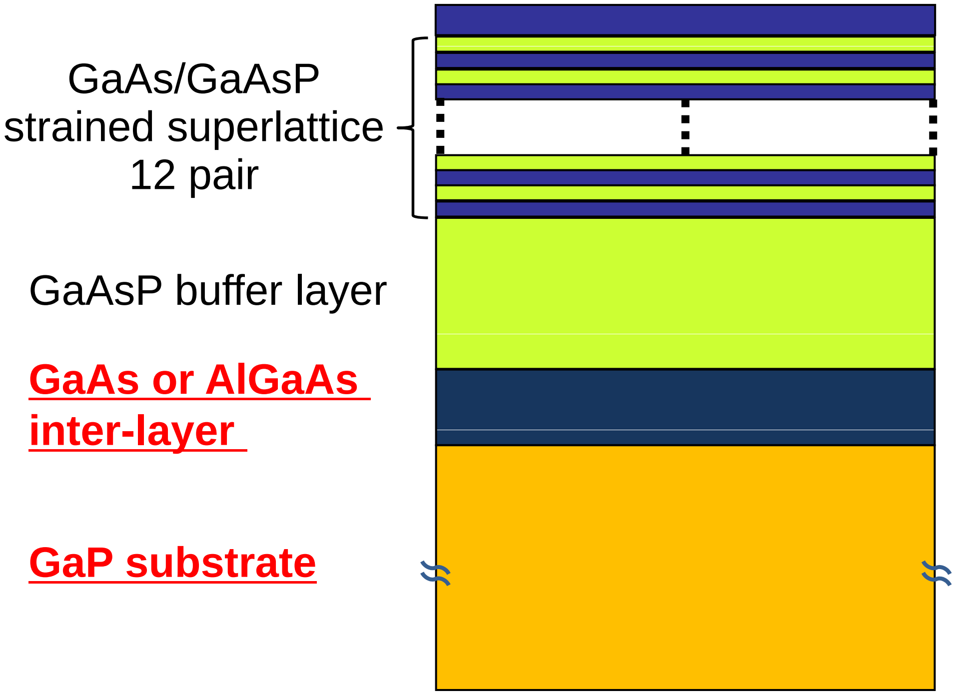
Pump laser light energy: **1.4~1.8 eV**

GaAs band gap energy is smaller than the pump laser light energy, and irradiation through the substrate is impossible.
On the other hand, GaP is transparent to pump laser light, and transmission-type photocathode is possible.

However、GaP lattice constant (5.4512Å) < GaAs lattice constant (5.6533Å)
There is a big problem in photocathode fabrication

Transmission-type photocathode

Transmission-type photocathode structure



Growth conditions

Growth method: MOVPE,

Growth temperature : 660°C,

Reactor pressure: 76 Torr,

V/III: 15,

Source materials : TEG, TBP, TBA.

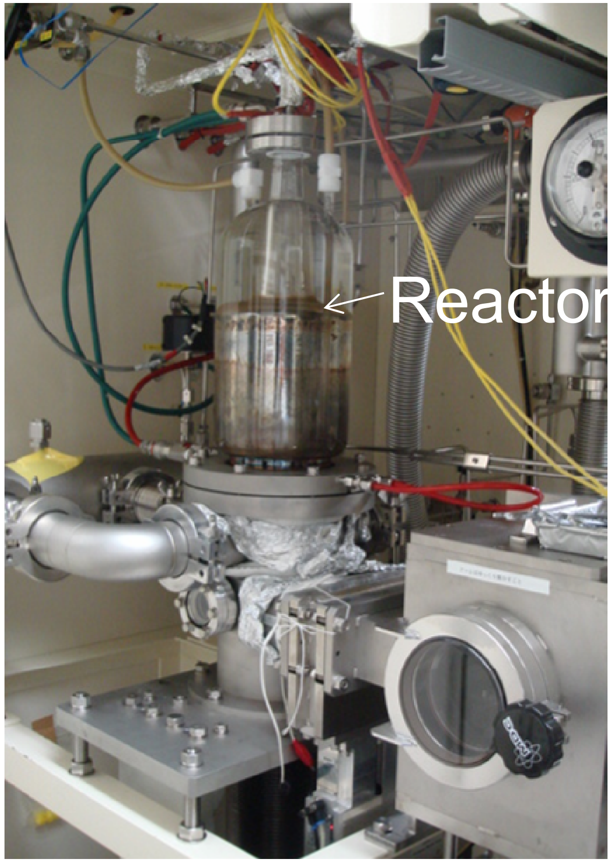
Flow rates:

For GaAs,
TEG: 9.5 μmol/min,
TBA: 143 μmol/min.

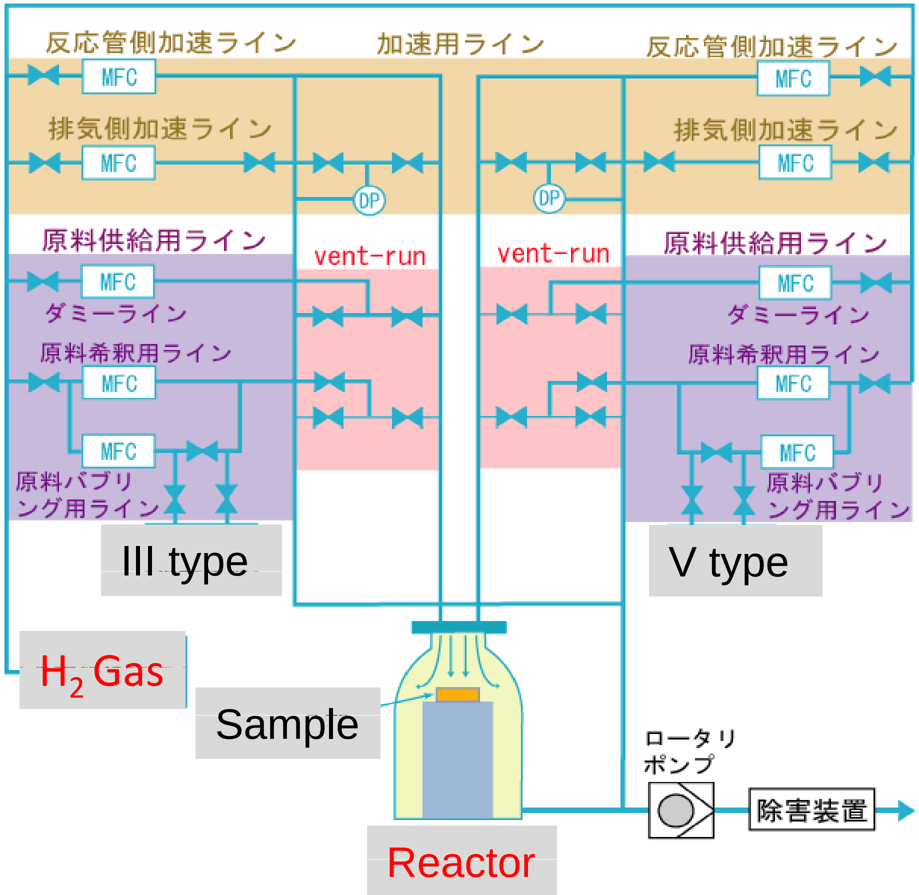
For GaAsP,
TEG: 9.5 μmol/min,
TBA: 28 μmol/min,
TBP: 114 μmol/min.

MOVPE System

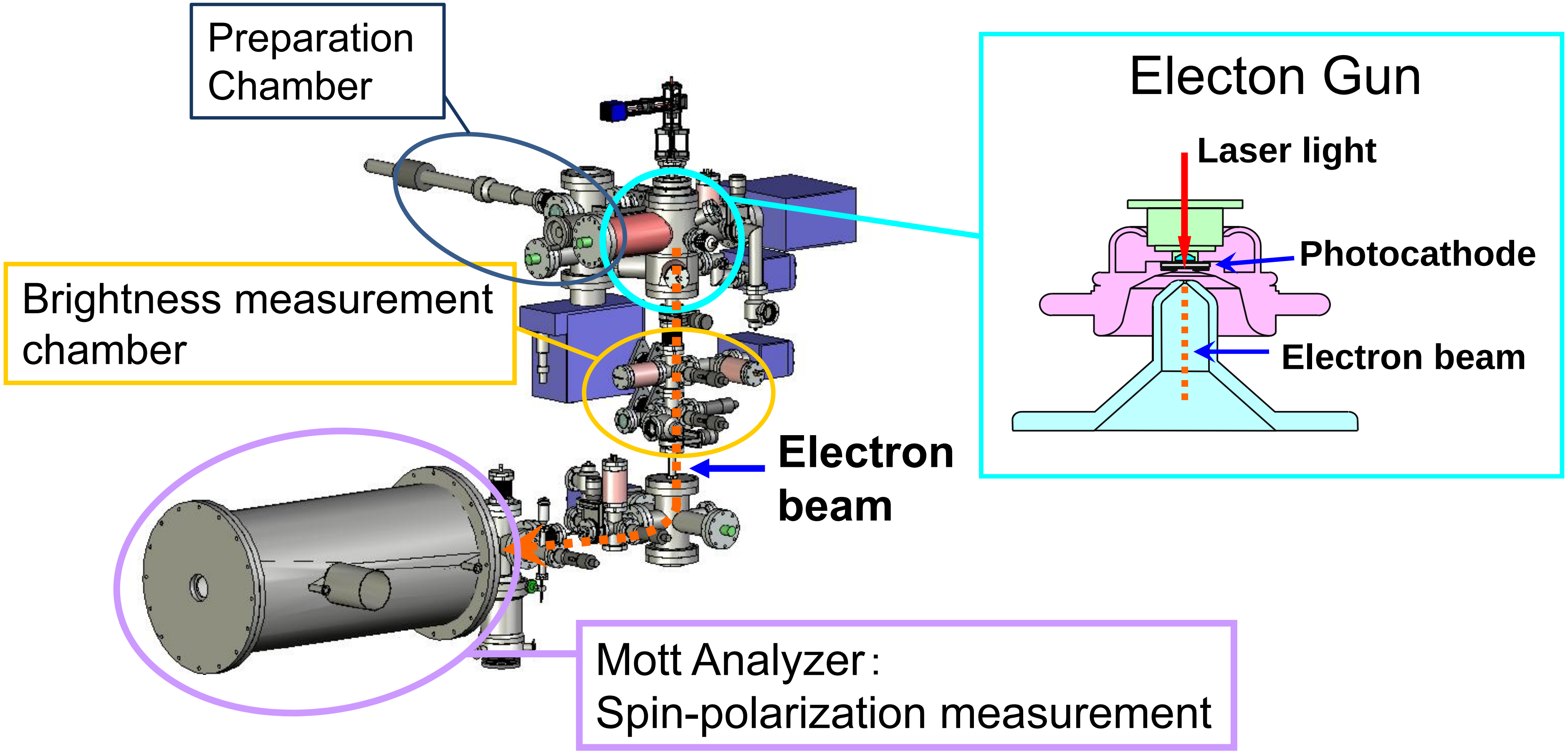
Image of reactor



Schematic view of MOVPE



Transmission-type electron gun

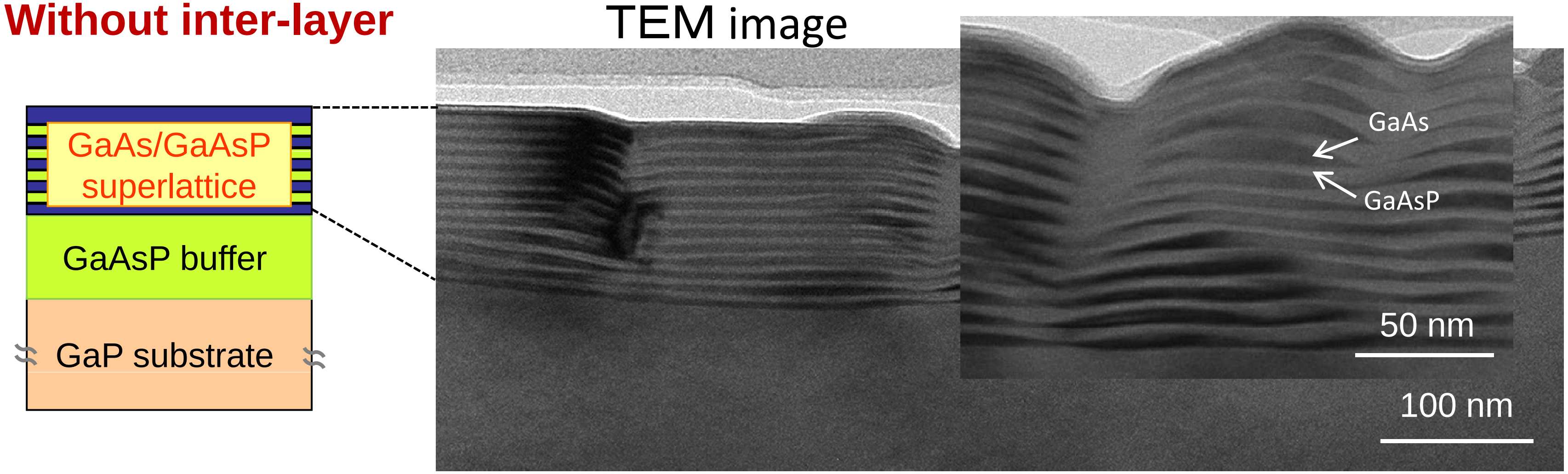


Transmission-type electron gun was designed and fabricated at Nagoya University

Effect of inter-layer

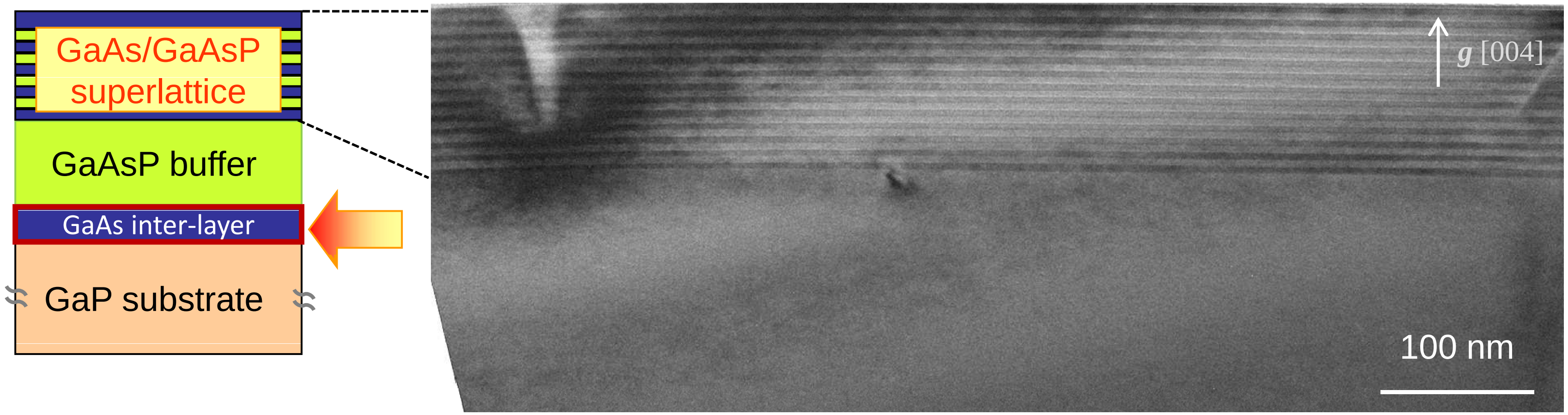
Without inter-layer

TEM image



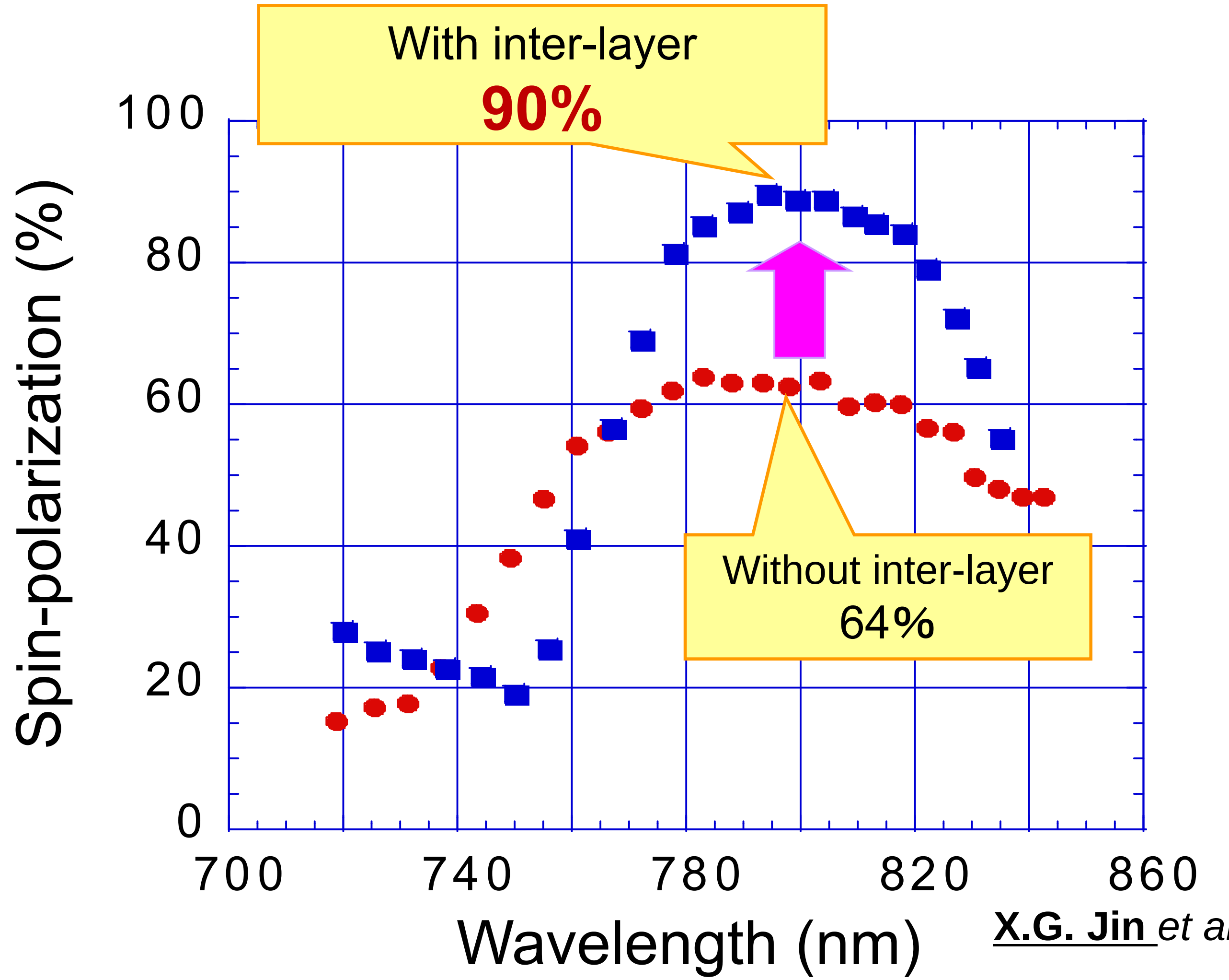
With inter-layer

TEM image



<u>X.G. Jin</u> *et al*. JAP **108** (2010) #094509

Spin-polarization measurement



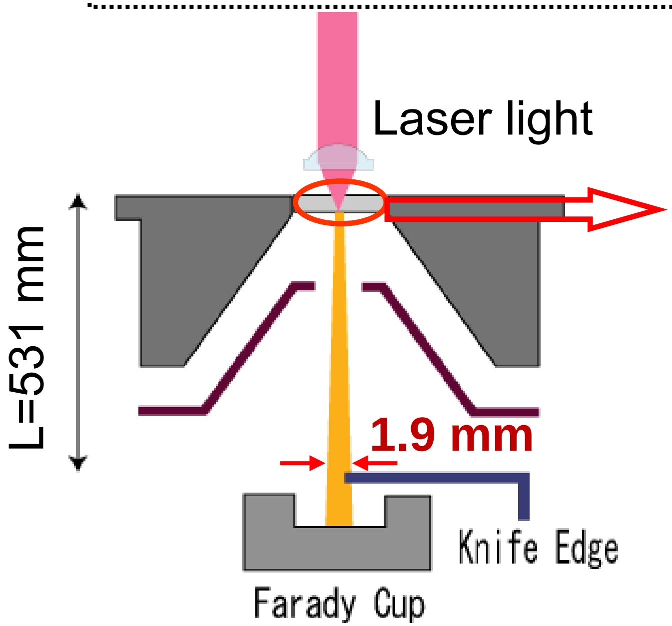
X.G. Jin *et al*. APEX **1** (2008) #045002

The maximum spin-polarization of 90% was achieved in transmission-type photocathode.

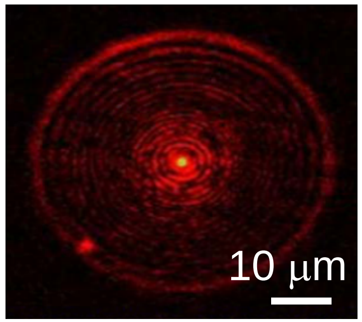
Brightness measurement

$$\text{Brightness} = \frac{I}{S \cdot \Omega} = \frac{I}{\pi r^2}\,\frac{L^2}{\pi(R-r)^2}$$

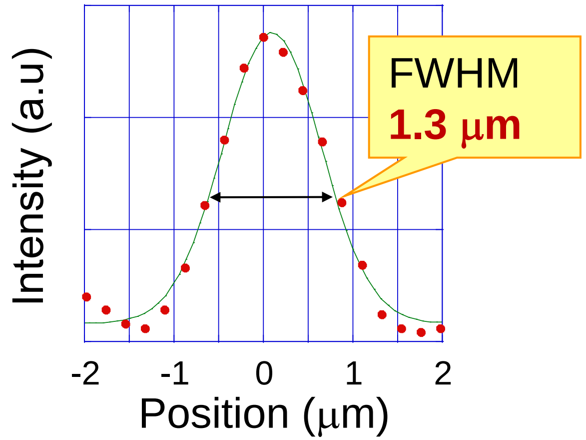
I: electron beam current
r: electron beam source radius on photocathode
R: electron beam radius
L: length between photocathode and knife



Laser spot image on photocathode back side



Laser spot profile



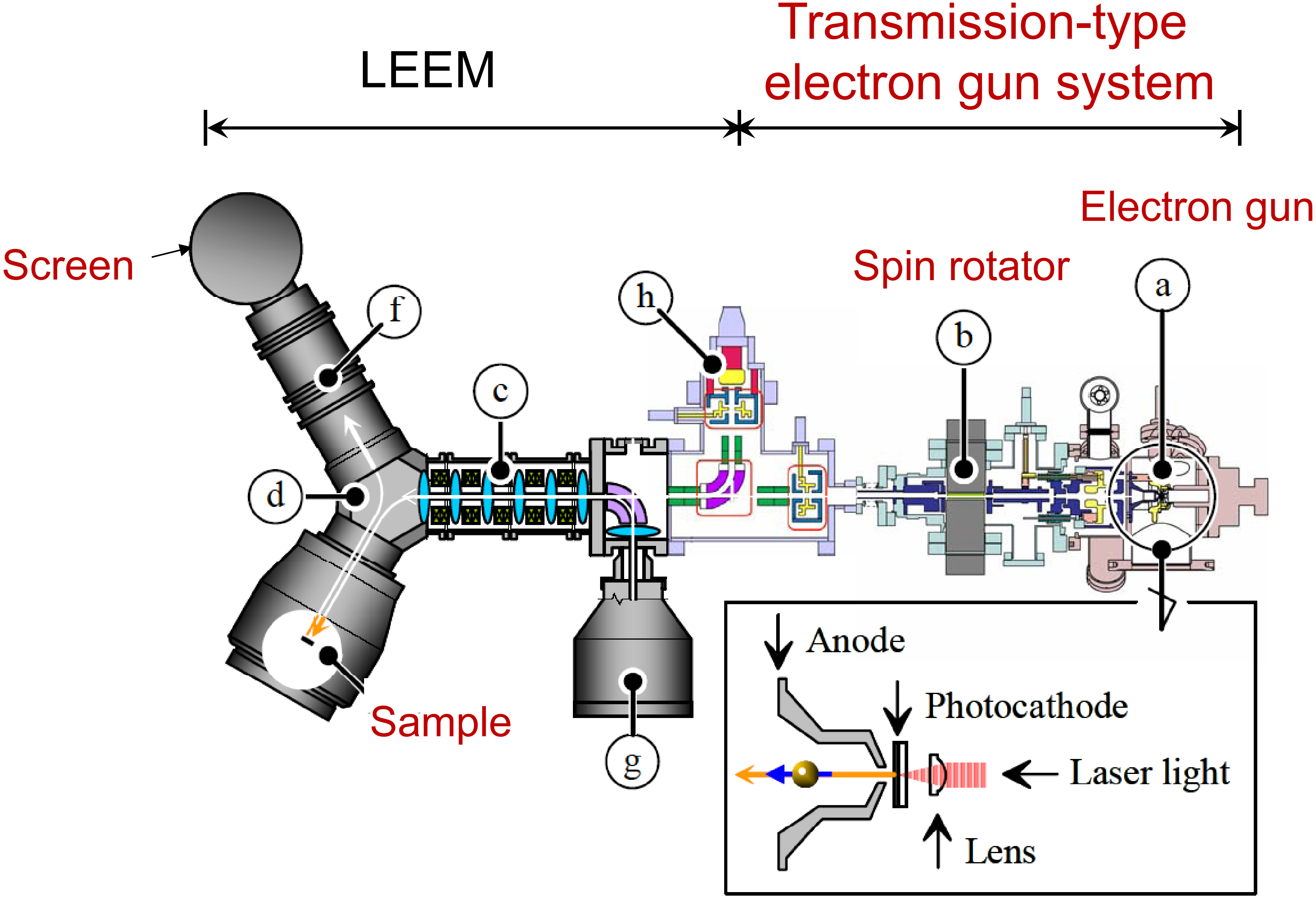
Laser spot diameter: **1.3 μm**, Electron beam current: **3.2 μA**, Electron beam diameter: **1.9 mm**.

The brightness is **1.3×10^{7} A·cm^{-2}·sr^{-1}**. It is by **10000 times** higher than that of the conventional reflection-type photocathode.

Life time of photocathode

Initial current (μA)	Current density (mA/mm^2)	1/e Life time (hour)
3	82	36
2	55	50
1	27	55

New SPLEEM



LEEM
Transmission-type
electron gun system
Electron gun
Spin rotator
Screen
a
b
c
d
f
g
h
Sample
Anode
Photocathode
Laser light
Lens

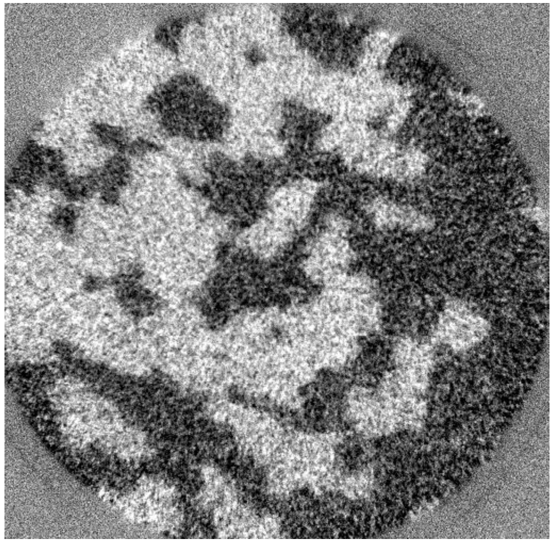
SPLEEM images

Specimen : Co 10 ML on W(110) substrate

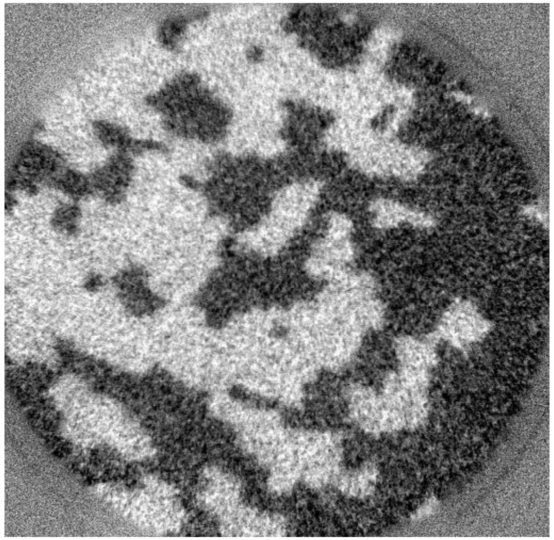
View area: 6 μm

Exposure time :

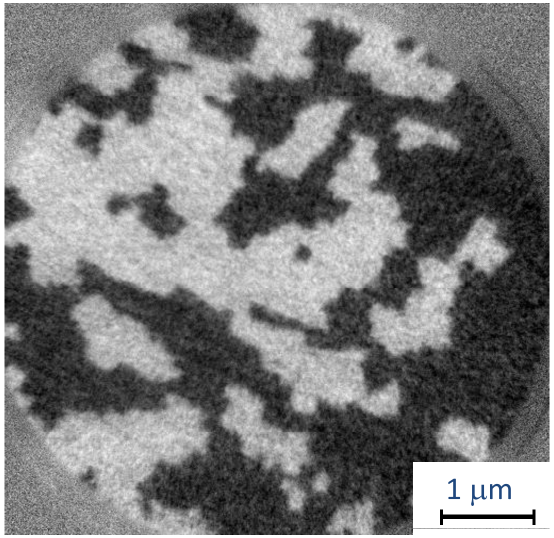
0.02 sec



0.04 sec



0.2 sec



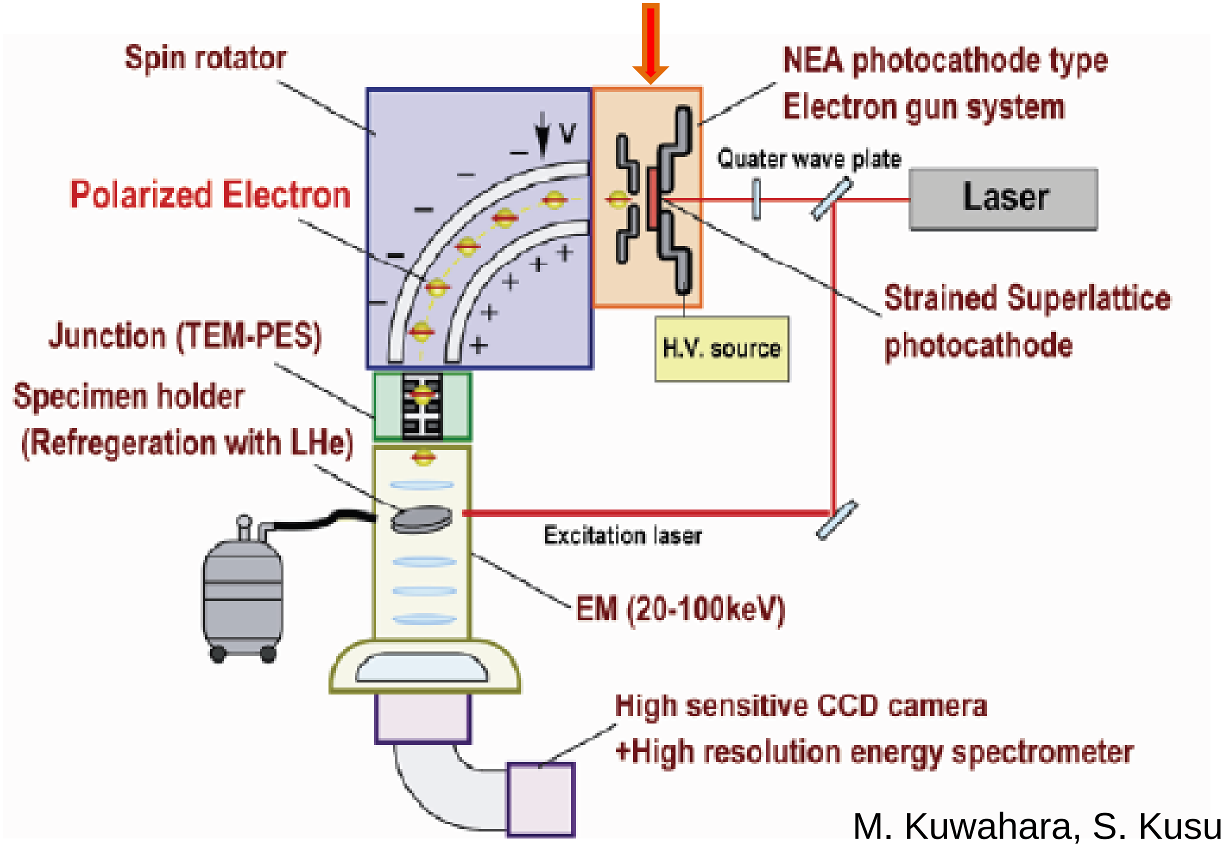
M. Suzuki *et al*. APEX **3** (2010) #026601

Clear magnetic image observed with **exposure time 0.02sec**.

Comparison: 1~10 s in conventional spin-polarized LEEM.

Spin-polarized TEM

Transmission-type Gun



M. Kuwahara, S. Kusunoki**, <u>X.G. Jin</u>** *et al*.
Appl. Phys. Lett. **101** (2012) #033102.

TEM with transmission-type spin-polarized photocathode is being developed at Nagoya University.

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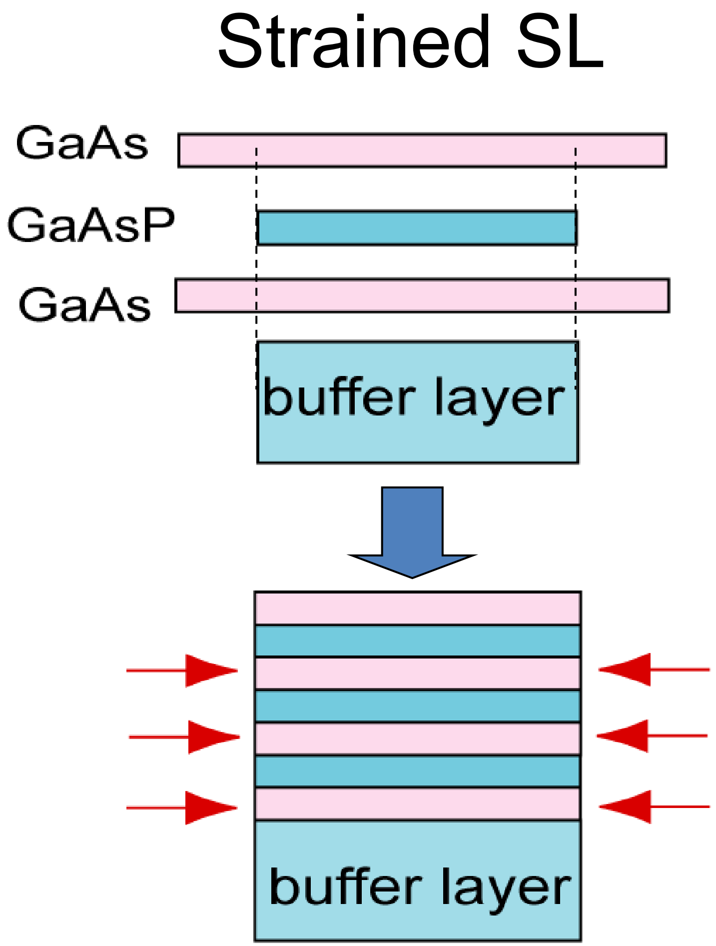
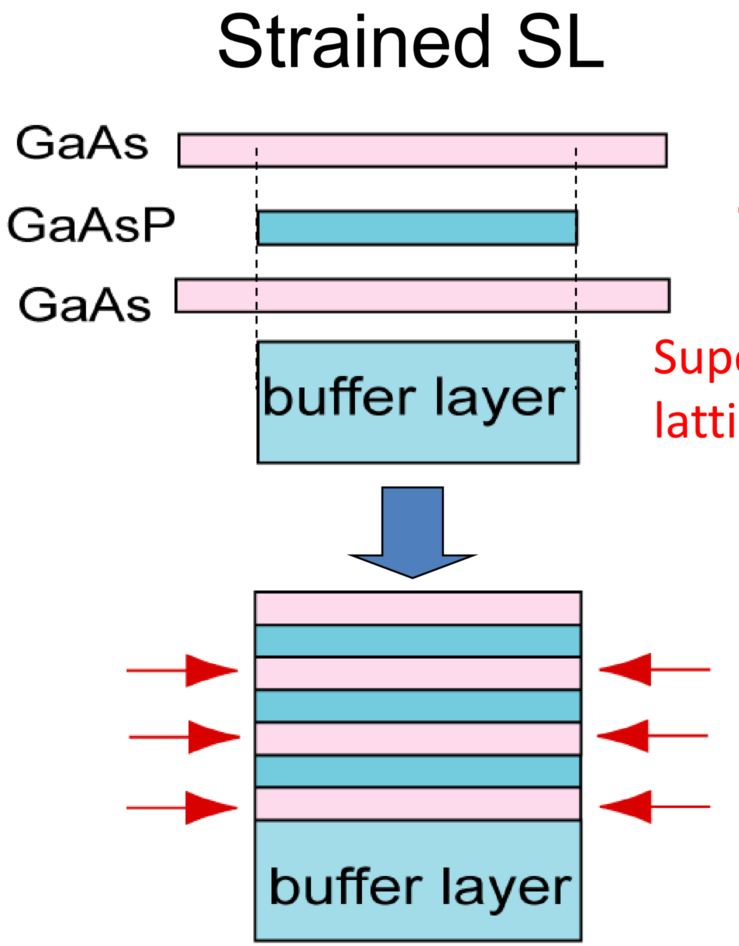
Problem of strained SL

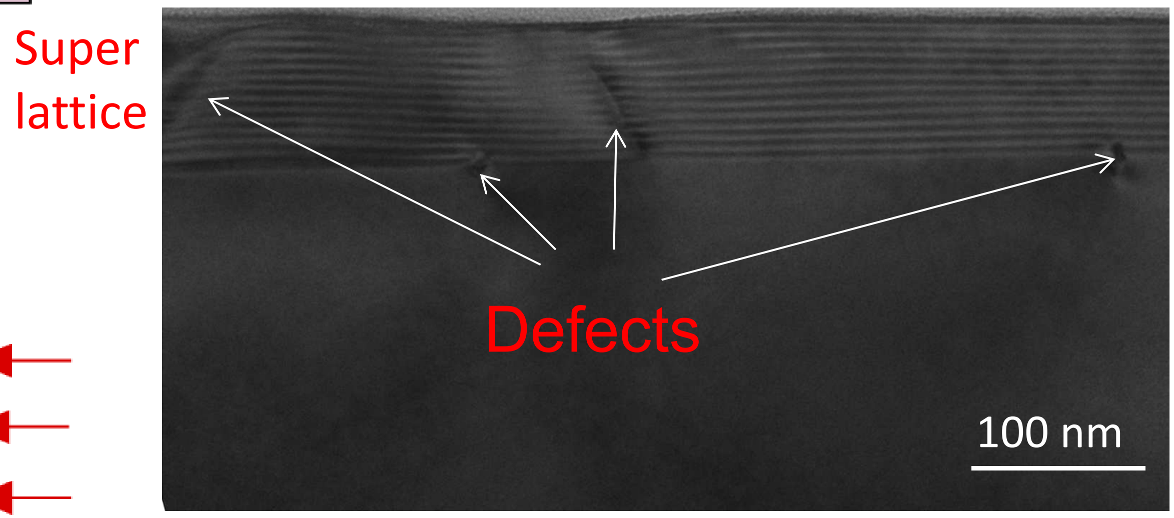


Strain is necessary for high spin-polarization.

Problem of strained SL



TEM image of
12 pair GaAs/GaAsP strained SL

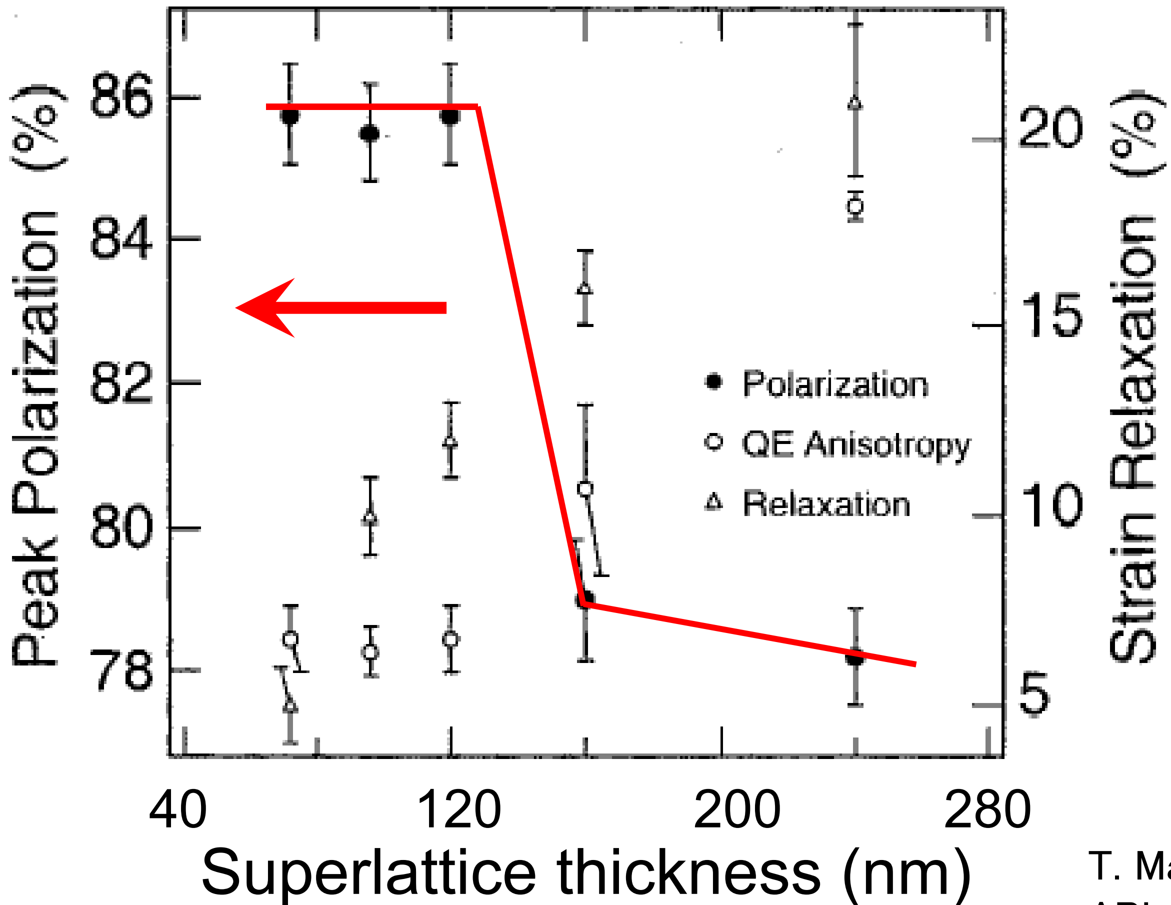


Strain is necessary for high spin-polarization.

Strain relaxation results in defects introduction.

Spin-polarization change with SL thickness

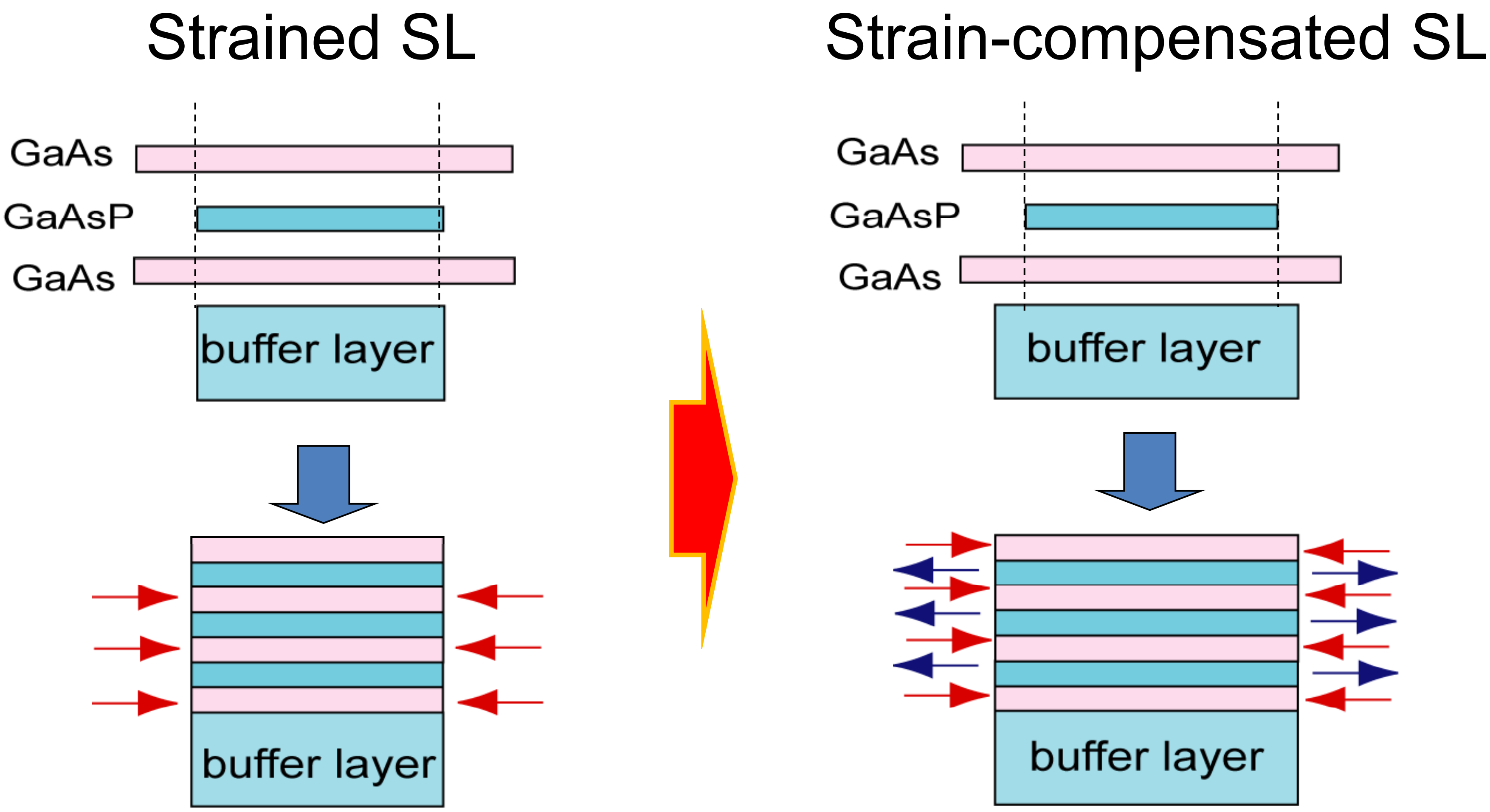
GaAs/GaAsP strained superlattice



T. Maruyama *et al.*, APL **85** (2004) 2640.

Thinner thickness, Worse crystal quality → Lower quantum efficiency

Advantage of strain-compensated SL



Strain-compensated SL prevents strain relaxation.

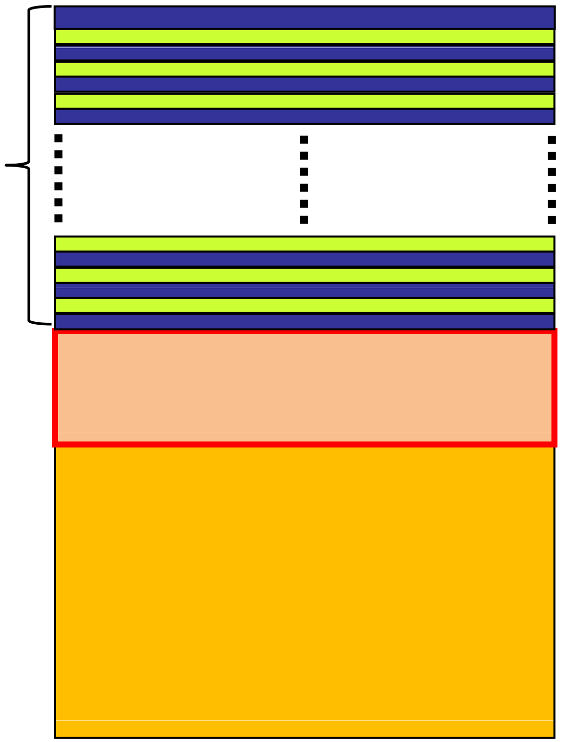
Strain-compensated SL fabrication

GaAs/GaAsP strain-compensated SL structrure

GaAs (4 nm)/
$GaAs_{0.62}P_{0.38}$ (4 nm)
Superlattice
12 pair~ 90 pair

$Al_{0.1}Ga_{0.9}As_{0.81}P_{0.19}$
buffer layer

GaP Substrate



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For GaAs,	For GaAsP,
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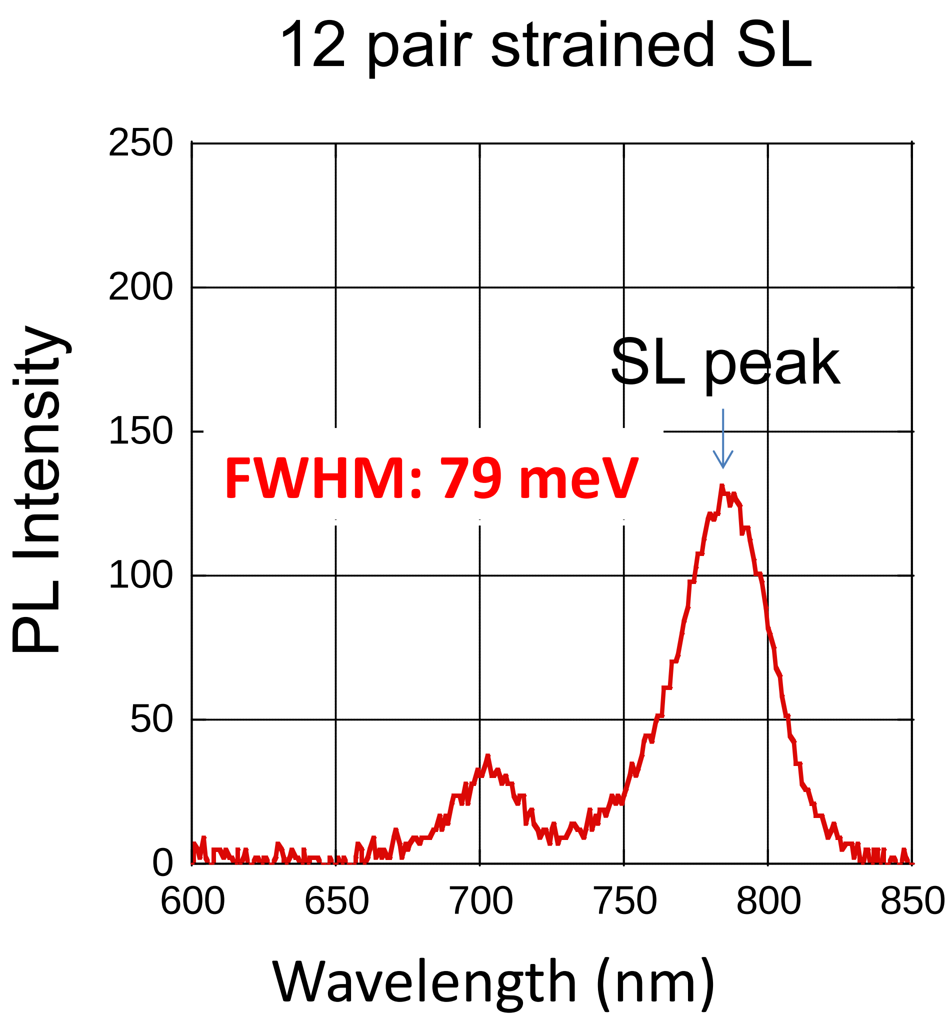
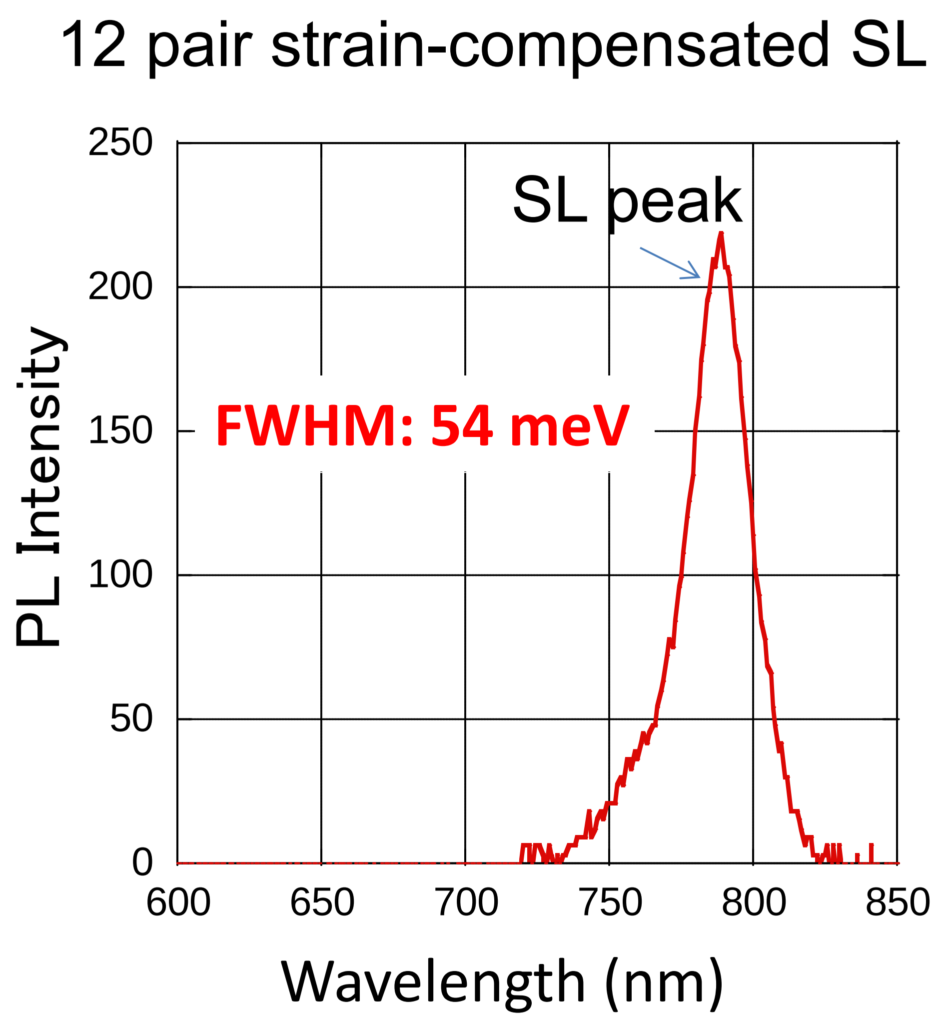
TBA: 143 μmol/min.	TBA: 28 μmol/min,
	TBP: 114 μmol/min.

<u>**X.G. Jin**</u> *et al*. APEX **6** (2012) #015801

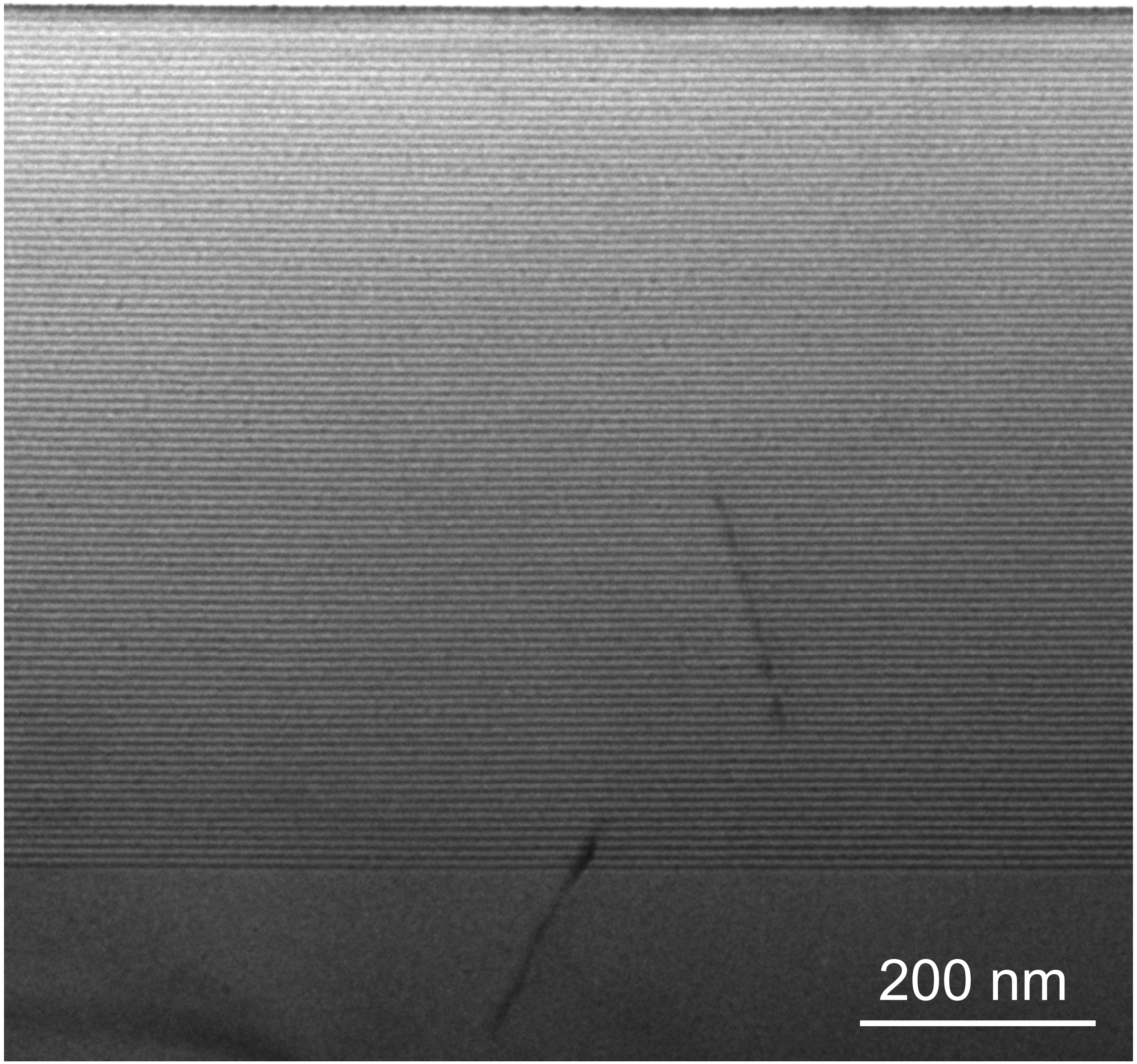
PL Measurement



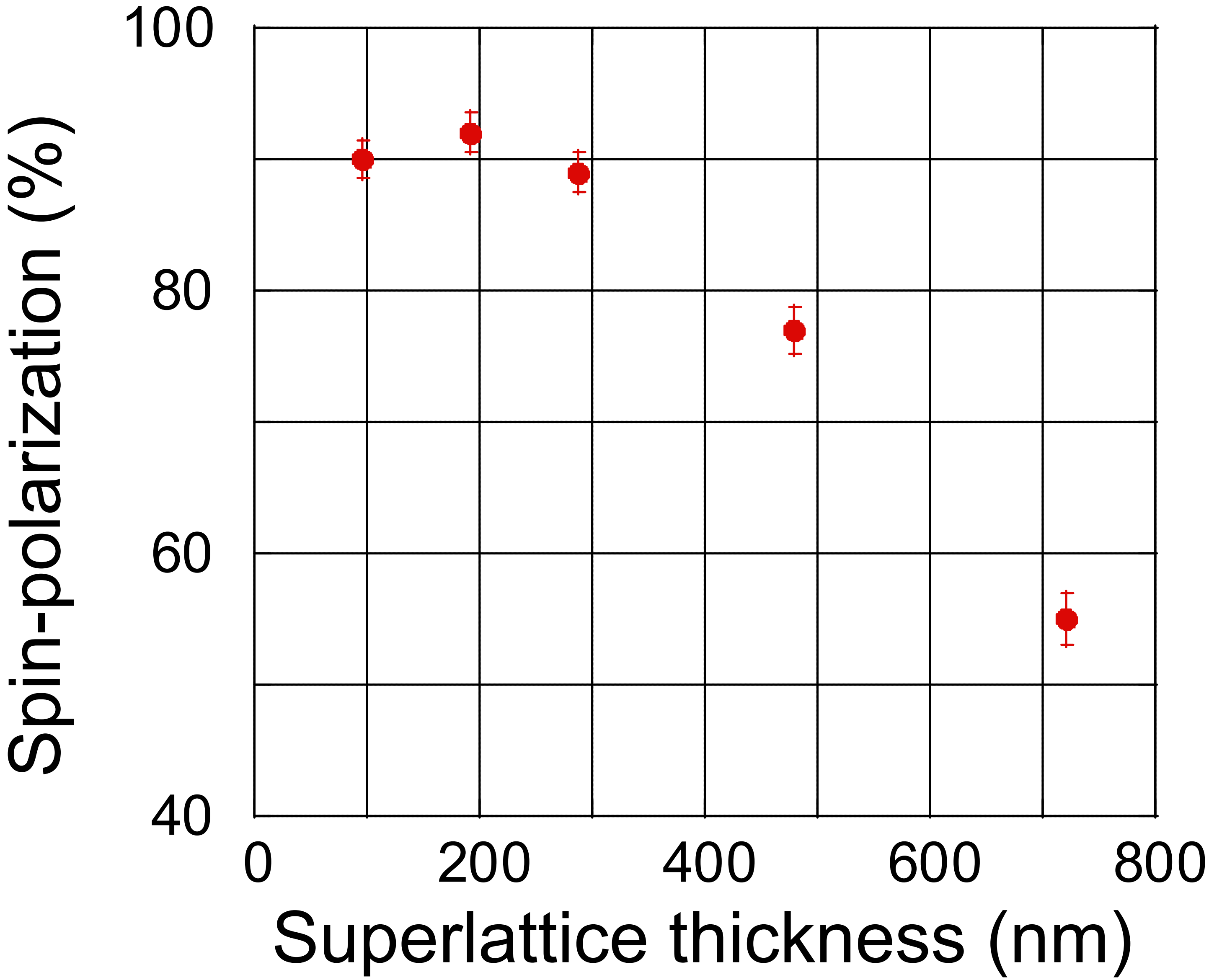


TEM image of strain-compensated SL

GaAs/GaAsP strain-compensated SL (90 pair)



Spin-polarization change with SL thickness

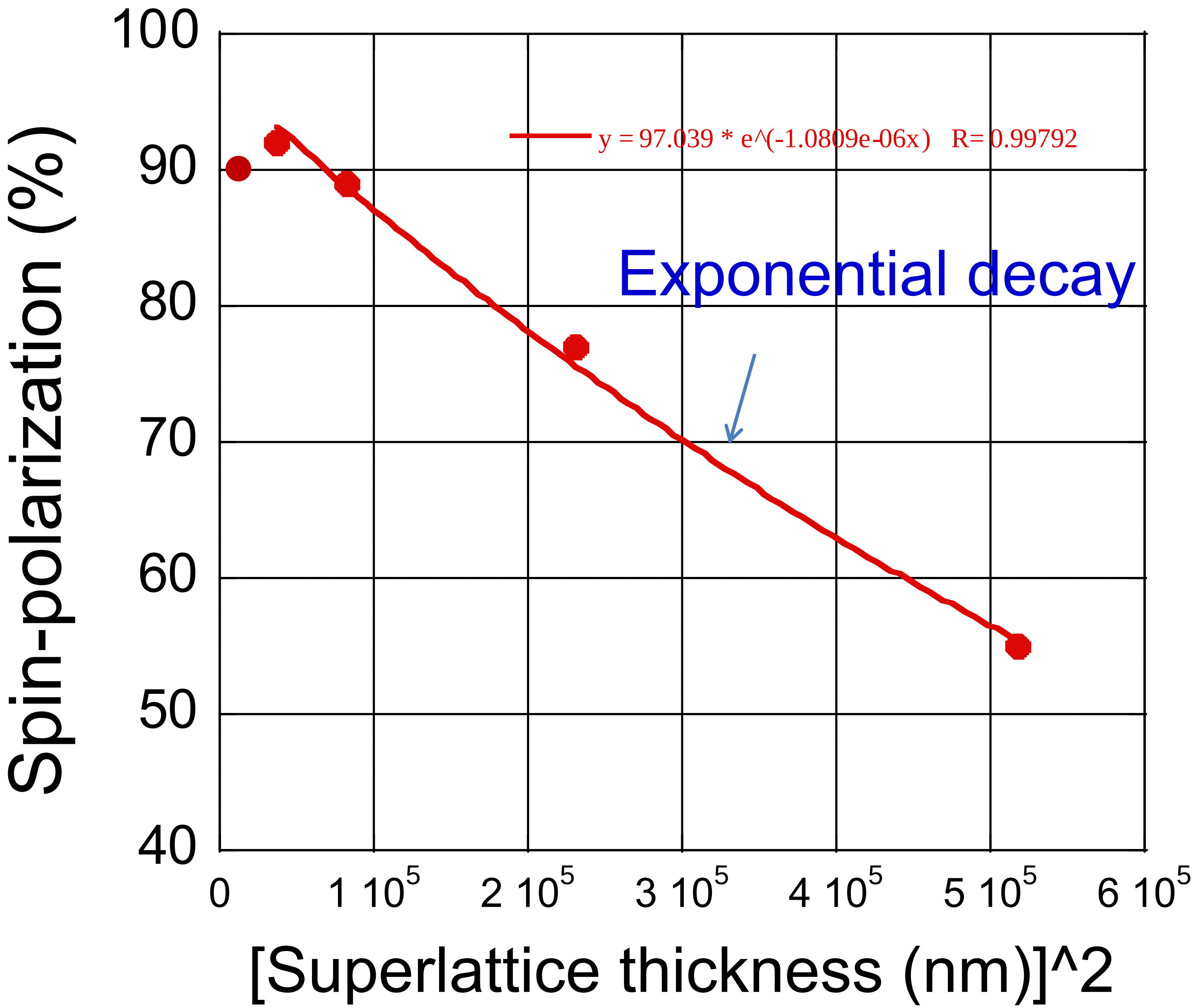


Electron transport can be described by diffusion model:

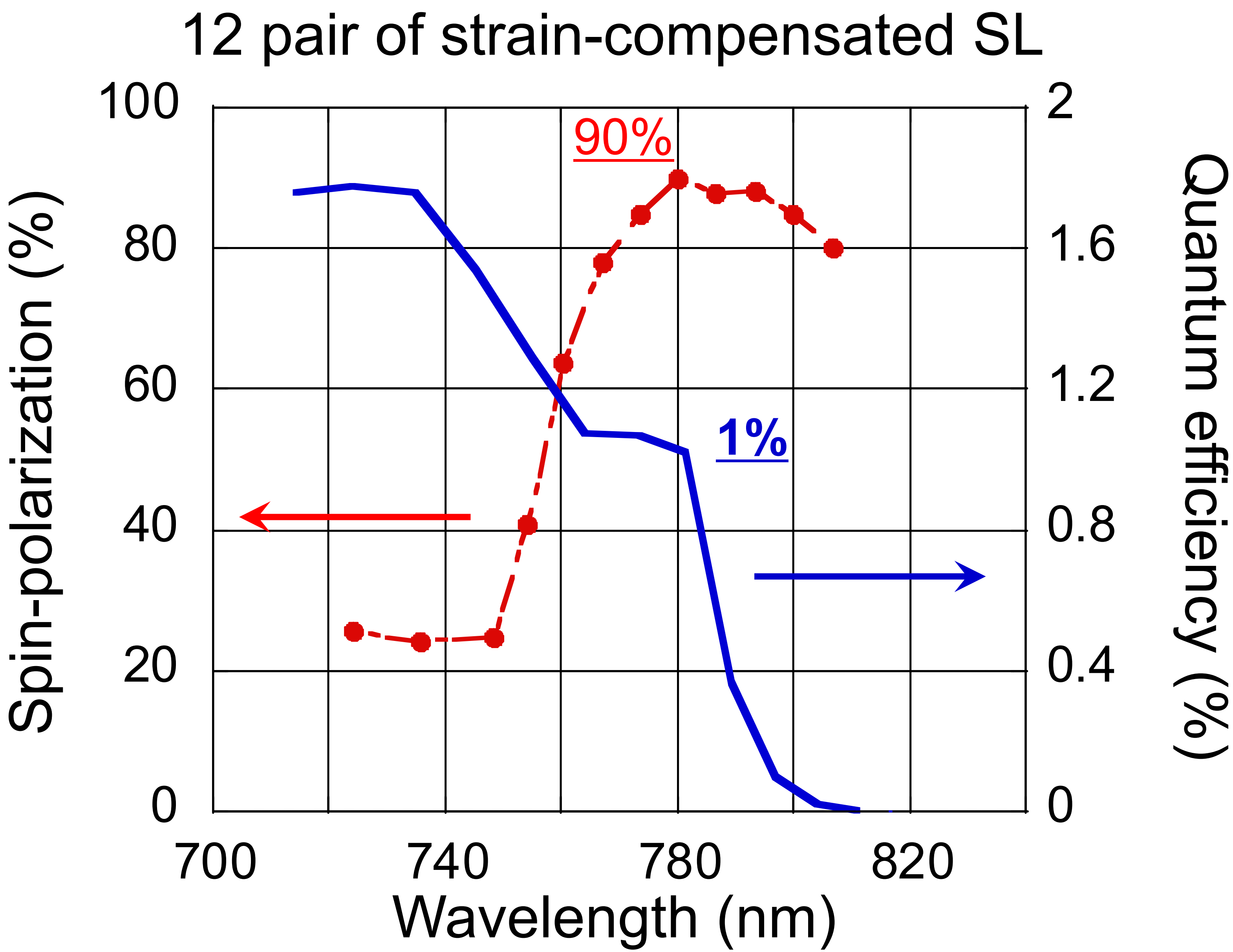
$$t = L^2/D$$

t , transport time;
L, thickness of the activity layer;
D, diffusion constant.

Spin-polarization with SL thickness



High quantum efficiency



Conclusion

- Transmission-type GaAs/GaAsP superlattice photocathodes were designed and fabricated.

- A super-high brightness ($1.3\times10^{7}\ A\cdot cm^{-2}\cdot sr^{-1}$) and a high spin-polarization (90%) of electron beam was achieved.

- High performance GaAs/GaAsP strain-compensated Superlattice photocathode were designed and fabricated.

- High spin-polarization (90%) and high quantum efficiency (1%) were achieved from strain-compensated superlattice.

Future work

- Quantum efficiency changes by superlattice thickness will be clarified.
- Transport time of excited electrons will be measured.